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Predicting Duff Consumption From Prescribed Burns on Conifer Clearcuts in Western Oregon and Western Washington

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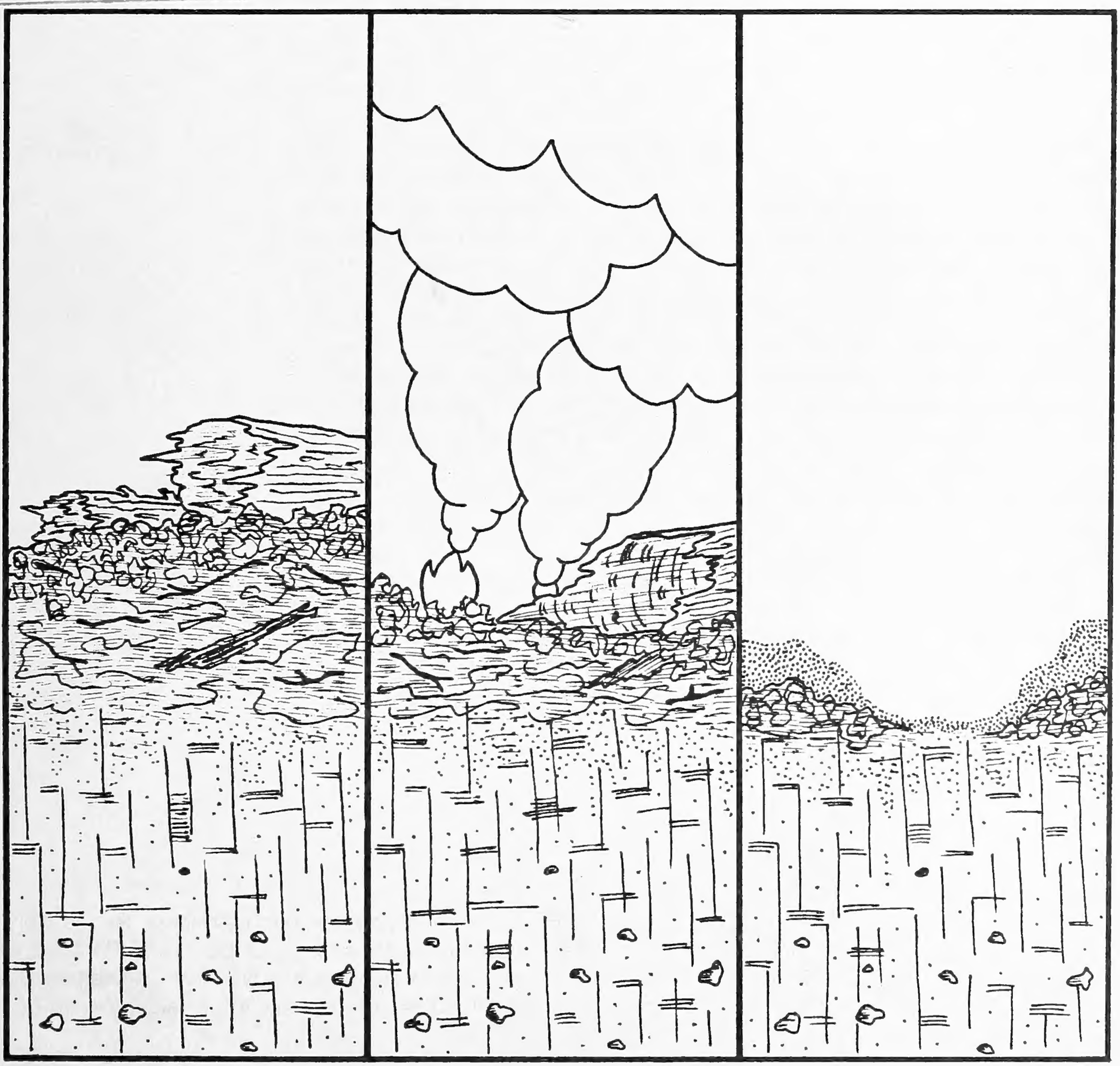

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Abstract

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Duff consumption by fire was studied on 15 cable-yarded clearcut units in western Oregon and western Washington. Equations are presented that predict duff consumption (in depth reduction and weight loss) from loading, consumption, and moisture of large fuels, and days since significant precipitation. When more than 25 days elapsed since 1.3 cm rainfall, the effect of large fuel loading on duff consumption diminished. Duff consumption was dependent on the diameter reduction of large fuels when there had been no rain for at least 25 days. The results indicated that duff consumption can be reduced by removing large fuel before the burn, scheduling the burn under moist conditions, or both. Methods are demonstrated to prescribe the proper level of fuel removal and moisture regime at time of burn to achieve a given level of duff consumption.

Keywords: Duff consumption, duff reduction, fire effects, prescribed burning, duff moisture, mineral soils, clearcuts.

Summary

Duff consumption by broadcast fire was studied on 15 cable-yarded clearcuts in western Oregon and western Washington. Units were divided into treatment blocks where either the amount of large fuels (greater than 7.62 cm diameter outside bark (d.o.b.)) or the moisture content of large fuels varied within the unit. Duff consumption was predicted from large fuel loading, consumption, moisture content, and days since rainfall. Prediction of duff consumption was enhanced by dividing the data into two populations: burns conducted less than 25 days since rainfall and burns conducted more than 25 days since rainfall. The duff consumption from burns in the first population depended on consumption of large fuels. Duff consumption depended on the diameter reduction of large fuels on burns that had not received rainfall for more than 25 days.

Mineral soil exposed during burns was predicted from preburn duff depth and days since rainfall.

The results suggested that savings in duff consumption can be achieved by removing large fuel before the burn, by scheduling the burn under moist conditions, or both. Methods are demonstrated for prescribing the proper level of fuel removal and moisture regime at the time of burning to achieve a given level of duff consumption.

Contents

Introduction

In this paper, we quantify (1) the effects of wood removal on the consumption of duff during prescribed burning and (2) the relationship between fuel loading and moisture content with regard to duff consumption. Forest managers in the Pacific Northwest prescribe fire as a treatment after timber harvest to reduce wildfire hazard, control competing vegetation, and facilitate planting. Even though fire has been proven to be a cost-effective tool for meeting these objectives, it has some undesirable effects. Burning the forest floor contributes to emissions during prescribed burns, reduces nutrient pools, and increases erosion hazard through exposure of mineral soil. The severity of these impacts depends on the duration and intensity of the fire, which in turn depend on the amount and moisture content of woody fuels. New markets have developed and are increasing for alternative wood products, including new fiber products and fuel wood for industrial and home consumption. This has led to removal of large amounts of wood from harvest sites—wood that would otherwise burn during site treatment. Hence, removing large amounts of wood from clearcuts will reduce duff consumption and allow the manager to meet site treatment objectives. The results of this study should enable managers to evaluate the effectiveness of increased wood utilization in reducing the negative impacts of prescribed burns.

The mantle of decaying organic matter above the forest soil (litter, fermentation, and humus layers, hereafter referred to as "duff") provides benefits to site productivity and soil stability. It serves as a protective layer by insulating the soil from temperature extremes, by retaining moisture, and by protecting the soil from erosion. Duff acts as a nutrient sink; the duff stores nutrients accumulated by the stand over the years and releases these nutrients to the forest as decay progresses. In some ecosystems, most of the nitrogen used in support of timber growth comes from this mantle.

Duff is disturbed to various degrees by timber harvesting; how much disturbance depends on the yarding system used and the slope of the harvest unit. Prescribed fire, used to treat the site for fire hazard reduction, brush control, and generation of planting sites, has the greatest potential to disturb duff of any management activity. Burning removes duff and exposes the mineral soil to erosion and temperature extremes. Nitrogen, one of the nutrients in short supply in the Pacific Northwest, is volatilized during the burn. Furthermore, duff consumed during a burn can contribute to over half of the particulate emissions from the burn (Sandberg 1984). On sites where the duff is exceptionally thick, managers may want to remove a portion of this mantle to ensure that seedlings are planted in mineral soil and that water can penetrate to their roots. Whether the objective is to retain or remove the duff, equations that predict duff consumption from fuel loading and moisture content are needed to set accurate burning prescriptions and to evaluate the utility of removing woody fuel before burning. The purpose of this study was to develop equations that will be applicable to conifer clearcuts in western Oregon and western Washington.

Review

The Role of Moisture in Duff Consumption

The amount of duff consumed during a prescribed burn depends on the moisture profile of the duff and on the amount and duration of heat from the burning woody fuel. Duff will burn independently of heat provided by burning woody fuel at a moisture content of 30 percent (Shearer 1975). The amount of heat needed to draw off moisture to that level depends, of course, on how wet the duff is before ignition. If a dry layer exists on the surface, it may reduce heat penetration in the duff profile, and duff consumption will be dependent on fire duration.

Predicting duff moisture.—The duff moisture profile depends on a number of physical properties, such as hydraulic conductivity and porosity (Fosberg 1977), topographic position (Hillhouse and Potts 1982), and weather. For sites where the physical characteristics of the duff are relatively uniform (for example, pine stands created by severe wild fire), the duff moisture profile will be relatively uniform and predictable from weather data. The Canadian Duff Moisture Index (DMC), developed for jack and red pine (*Pinus banksiana* Lamb. and *P. resinosa* Ait.), predicts duff moisture based on precipitation, temperature, and relative humidity (Van Wagner 1970). The DMC is based on empirical evidence that pine duff dries exponentially. Van Wagner (1982) established that the rate of drying is independent of initial moisture content. Although DMC has been a successful predictor for moisture content of pine duff, it has not been proven successful for west-side Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sargent) duff, which is much more variable across a unit.

In a laboratory experiment on five conifer duff types from California, Stocks (1970) found that 1.3 cm of rainfall wet the litter layer as well as did 5.1 cm of rainfall, and that 1.3 cm of rainfall was sufficient to raise the moisture content of a dry litter layer to 120 percent. The wetting of the litter to that moisture content should preclude ignition of duff in the absence of heat from woody fuel (Sandberg 1980).

Cooper[1/] studied drying of individual duff types and depths. Duff beds consisting of either litter and litter-derived humus (bulk density of 0.12 g/cm^3) or rotten material (bulk density of 0.18 g/cm^3) were constructed to depths of 5.1 cm and 10.2 cm. These beds were saturated and then allowed to dry in the laboratory. Preliminary results suggested that, under constant temperature and humidity, it takes 7 days (for duff derived from needles) to 16 days (for duff derived from rotten woody material) for the top 2.5 cm of duff to dry to 30-percent moisture content. Using an adjustment developed by Fosberg and others (1970) to extrapolate laboratory results to field conditions (where the diurnal flux of temperature and humidity prolong the drying period), Cooper concluded that 25 days are needed to dry the top 2.5 cm of duff to a moisture content of 30 percent. At this moisture content, duff should burn independently of woody fuel loading.

[1/]Unpublished Report, 1985, "The second report on progress made toward predicting the occurrence of a dry lower duff layer," by Kathy L. Cooper, U.S. Department of Agriculture, Forest Service, Forestry Sciences Laboratory, 4043 Roosevelt Way, NE, Seattle, WA 98105.

Predicting duff consumption from moisture variables.—Published equations for predicting duff consumption from moisture variables are listed in table 1. Van Wagner (1972) relates weight of duff consumed during underburning to fire duration and the inverse of duff moisture. Chrosciewicz (1978a, 1978b) and Blackhall and AuClair (1982) also predict duff consumption from DMC. Beaufait and others (1977) show a weak dependence of duff consumption on upper duff moisture and the Buildup Index. Brown and others (1985) predict duff consumption on Montana clearcuts from measured duff moisture and predict moisture indices with variable success (correlation coefficients 0.48 to 0.76). The range of fuel moisture and preburn depths are considerably less than those prescribed for clearcut burns on the west side of the Cascade Range.

Table 1—Published equations predicting duff depth reduction from prescribed burns

Source, location, and species	Equation 1/	R^2	$s_{y \cdot x}$	N
Beaufait and others (1977), Montana, larch and Douglas-fir	DUFRED = −4.15 − 0.0022 UDMC − 0.05 BI + 1.31 $\sqrt{BI}$	0.53	1.2	76
Blackhall and AuClair (1982), northern British Columbia, white spruce and subalpine fir	DUFRED = −28.74 + 0.75 BEFDUFF + 2.78 LOGDMC + 9.63 LOGDC	.65	.9	45
Brown and others (1985), Montana, larch and Douglas-fir	DUFRED = 2.61 − 0.023 LDMC + 0.42 BEFDUFF	.76	.8	60
Chrosciewicz (1978b), Manitoba, jack pine	DUFRED = 2.78 − 0.053 DMC; BEFDUFF less than 4 cm	.93	.2	10
	DUFRED = 9.22 − 0.094 DMC; BEFDUFF greater than 8 cm	.90	.4	5
Chrosciewicz (1978a), Saskatchewan, jack pine	DUFRED = 3.42 − 0.048 DMC; BEFDUFF = 4 cm	.74	.3	8
	DUFRED = 4.03 − 0.042 DMC; BEFDUFF = 6 cm	.74	.25	8
Sandberg (1980), Oregon and Washington, Douglas-fir and western hemlock	DUFRED = −0.16 + 1.76 $\sqrt{DRED}$	.71	.48	11
	DUFRED = 6.67 − 0.13 NFDR-Th	.78	.47	10

1/ BEFDUFF = preburn duff depth in centimeters,
BI = Buildup Index,
DC = Drought Code,
DMC = Duff Moisture Code,
DRED = diameter reduction of woody fuels in centimeters,
DUFRED = duff depth reduction in centimeters,
NFDR-Th = moisture content of fuels larger than 7.6 cm predicted by the National Fire-Danger Rating System, in percent, and
UDMC (LDMC) = upper (lower) duff moisture content in percent.

Sandberg (1980) adapted Van Wagner's theory to underburning Douglas-fir in partial-cut stands in western Oregon and Washington. He predicts duff consumption from diameter reduction of large fuels ($r^2 = 0.78$) and from the National Fire-Danger Rating System (Deeming and others 1977) prediction of thousand-hour fuel moisture (NFDR-Th) ($r^2 = 0.78$). When applied to clearcuts, his predictors are not always successful (Little and Klock 1985, Little and others 1982). This may be the result of differences in temperature extremes and, hence, drying patterns on clearcuts versus partial cuts. Duff loadings on clearcuts are often more variable within a unit than in partial-cut stands. This is the result of large deposits of litter from crown material, increased disturbance from skid roads, and large amounts of rotten woody material incorporated in the duff from cull material left during felling and harvesting. Consequently, duff consumption on clearcuts is highly variable because of the high variability in duff loading, duff moisture, and fuel consumption (for example, large rotten logs that smolder for prolonged periods). There is a clear need for predictors of duff consumption that are tailored to clearcuts.

The Role of Loading and Consumption of Woody Fuel in Duff Consumption

Sandberg[2/] hypothesized that consumption of duff by fire is dependent on woody fuel consumption or woody fuel diameter reduction. When the duff bed is wet (NFDR-Th greater than 25 percent), total heat load (as measured by fuel consumption) will determine how much duff is consumed. By removing large fuels, the amount of fuel consumed will be reduced and, hence, the amount of duff consumed will also be reduced. When the duff bed is dry (NFDR-Th less than 25 percent), the upper duff serves as an insulating layer and reduces the penetration of heat into the duff. Under these conditions, the duration of fire (as measured by diameter reduction of large fuels) will determine how much duff is consumed. Fire duration is dependent on fuel moisture rather than on fuel loading.

Sandberg and Ottmar (1983) developed a set of equations that estimate the percentage of volume reduction by fire of large fuels in Douglas-fir and western hemlock units. The percentage of volume reduction (VRED) is based on the relationship between large fuel moisture (LGMC) and diameter reduction (DRED):

$$\mathrm{VRED} = 1 - (d - \mathrm{DRED})^2 / d^2 \text{, and}$$

$$\mathrm{DRED} = 14.43 - 0.274\ \mathrm{LGMC}\ ;$$

where d is the root mean square diameter of large fuels in centimeters, DRED is calculated in centimeters, and LGMC is a percentage.

Removing larger material from a unit would decrease d. Although a greater proportion of the remaining fuel would be consumed for a given moisture content, the total amount of fuel before burn would be reduced, which would reduce total fuel consumption.

[2/]Unpublished Report, 1979, "Predicting prescribed fire behavior," by David V. Sandberg, U.S. Department of Agriculture, Forest Service, Forestry Sciences Laboratory, 4043 Roosevelt Way, NE, Seattle, WA 98105.

In a case study, a unit where all material larger than 0.15 by 1.8 m was removed prior to burning (leaving 9.1 Mg/ha of large fuels) had less duff consumption than the comparison unit, which was logged to 0.2 by 2.4 m (37.7 Mg/ha of large fuels) (Little and others 1982). In subsequent work by Little and Klock (1985), six paired units that were yarded to 0.1 by 1.2 m and 0.15 by 1.8 m and two units that were yarded to 0.2 by 2.4 m were broadcast burned. There was no apparent pattern in duff consumption relative to diameter reduction or fuel loading on these units.

Predicting Mineral Soil Exposed During Prescribed Fire

The amount of mineral soil exposed during a prescribed burn depends on the amount of duff cover, on the depth of duff prior to ignition, and on the depth of duff consumed during the burn. For those ecosystems with uniform duff densities and cover, mineral soil exposure—like duff consumption—will be closely tied to duff moisture content, fuel consumption, and weather variables. Chrosciewicz (1978a, 1978b) was not able to establish a significant relationship between mineral soil exposed and DMC for burns of jack pine clearcuts. Brown and others (1985) found mineral soil exposed to be correlated with lower duff moisture ($r^2 = 0.58$). The highest degree of success to date was achieved by Sandberg (1980). He related mineral soil exposed to NFDR-Th ($r^2=0.76$) for units with less than 10.5 cm of average duff depth (10 units in all).

Methods

This study was conducted to determine the combined influences of fuel loading and moisture on duff consumption. To isolate the separate effects of loading and moisture content, some units were divided into treatment blocks where either loading or moisture were varied within the unit. Other units with only one treatment were burned to expand our data base for larger fuel loadings.

We measured duff consumption on 38 treatment blocks on 15 cable-yarded clear-cut units on National Forest (NF) and private lands in western Oregon and western Washington (fig. 1). The units spanned much of the geographical area and range of site conditions characteristic of the Douglas-fir zone. Elevation ranged from 400 to 1400 m; slope from zero to 35 percent. Douglas-fir and western hemlock comprised most of the slash on the units. Large fuel (greater than 7.6 cm diameter outside bark (d.o.b.)) loading ranged from 8.7 to 120.8 Mg/ha; fine fuel (less than 7.6 cm d.o.b.) loading ranged from 10.3 to 26.7 Mg/ha. Average duff depth ranged from 3.1 cm on a southwestern Oregon unit to over 17 cm on a western Washington unit (table 2).

Figure 1.—Location of clearcut units in western Washington and western Oregon that were burned for the duff reduction study.

Table 2—Locations of units, fuel loadings, and date of burn

Unit name (location)	Block	Yarding specification	Preburn fuels: 0-7.6 cm d.o.b.	7.6+ cm d.o.b.	Duff	Duff depth	Mineral soil exposed	Date burned
		m	--------- Mg/ha	---------	---------	cm	percent	month-day-year
Cataract (Siuslaw NF)	1	0.1 x 1.2	16.1	8.7	86.5	6.5	17	8-19-83
	2	.15 x 1.8	24.2	19.7	92.6	6.5	11	8-19-83
	3	.2 x 2.4	15.0	34.3	89.7	7.7	22	8-19-83
	4	.2 x 2.4	17.9	54.2	137.4	9.7	6	9-17-83
Maria (Siuslaw NF)	1	.1 x 1.2	16.1	18.4	105.4	7.6	6	8-21-83
	2	.15 x 1.8	10.3	12.1	67.7	5.0	19	8-21-83
	3	.2 x 2.4	15.2	44.2	134.7	9.7	3	8-21-83
	4	.2 x 2.4	25.3	38.8	116.1	8.4	0	9-21-83
North Slope 6 (Rogue River NF)	1	.1 x 1.2	22.2	13.7	67.7	5.1	4	7-15-83
	2	.15 x 1.8	19.5	24.2	69.3	5.0	3	7-15-83
	3	.2 x 2.4	18.4	50.7	70.2	5.3	1	7-15-83
North Slope 7 (Rogue River NF)	1	.1 x 1.2	19.1	10.5	68.1	5.0	5	7-13-83
	2	.15 x 1.8	16.4	16.4	38.1	2.8	7	7-13-83
	3	.2 x 2.4	19.1	27.6	47.7	3.6	6	7-13-83
North Slope 8 (Rogue River NF)	1	.1 x 1.2	19.5	8.7	59.2	4.2	6	7-14-83
	2	.15 x 1.8	22.0	35.2	75.8	5.6	2	7-14-83
	3	.2 x 2.4	26.7	29.6	49.3	3.5	4	7-14-83
Lower Grizzly (Umpqua NF)	1	.1 x 1.2	13.7	9.6	72.6	5.1	9	7-24-83
	2	.15 x 1.8	24.0	31.2	100.7	7.4	5	7-24-83
	3	.2 x 2.4	19.7	44.6	140.1	9.7	5	7-24-83
	4	.2 x 2.4	22.6	34.5	95.7	6.8	3	9-29-83
Yoncalla (Siuslaw NF)	1	.1 x 1.2	15.0	30.3	72.9	5.3	10	9-23-83
	2	.15 x 1.8	15.0	25.1	67.3	5.1	18	9-23-83
	3	.2 x 2.4	22.4	52.1	106.3	7.6	4	9-23-83
	4	.2 x 2.4	12.6	24.2	79.6	5.7	4	9-23-83
White Chuck (Mount Baker-Snoqualmie NF)	1	***	24.2	34.3	157.6	11.2	2	7-09-84
	3	***	22.4	34.5	118.8	8.4	5	7-27-84
Breakeven (Olympic NF)	1	***	15.9	50.7	227.5	15.0	9	7-15-84
	2	***	16.4	42.8	209.8	13.4	0	8-26-84
	3	***	15.5	63.7	244.1	16.1	1	7-30-84
	4	***	21.1	60.1	181.1	12.1	5	7-15-84
Beaver Bar (Mount Baker-Snoqualmie NF)	1	***	17.3	62.1	175.3	12.0	10	8-23-84
Rink (Mount Baker-Snoqualmie NF)	1	***	23.3	120.2	125.8	8.8	9	9-19-84
L 142 (Olympic NF)	1	***	13.5	34.1	46.0	3.3	14	7-18-84
High Divide (Weyerhauser)		***	17.3	22.4	112.1	7.8	4	9-17-84
Little Deschutes (Weyerhauser)		***	18.2	32.7	136.7	9.9	0	7-06-84
Twin Harbors #896 (Weyerhauser)		***	17.7	58.3	124.0	8.6	7	7-23-84

*** = no yarding specification.
--- = not applicable.

We burned the seven clearcut units in Oregon in 1983 (Cataract, Maria, Yoncalla Dumbell—Siuslaw NF; North Slope #6, #7, and #8—Rogue River NF; and Lower Grizzly #5—Umpqua NF). Each unit was divided into treatment areas that were designed to vary the loading of large fuels while holding moisture content and fine fuel loading constant. In this way the effects of different loadings of large fuel on duff consumption could be isolated. We delineated three 0.2-ha treatment blocks on each clearcut unit. Each treatment block within a unit was cable yarded to one of three specifications chosen to cover the anticipated range of management options. All woody fuel larger than the specified piece size (0.10 by 1.2 m, 0.15 by 1.8 m, or 0.2 by 2.4 m) was removed from the block. We burned the three adjacent treatment blocks simultaneously to ensure similar fuel moisture conditions. A fourth block, yarded to 0.2 by 2.4 m (holdover), was established on four of these units (Cataract, Maria, Yoncalla Dumbell, and Lower Grizzly #5), and burned under moisture conditions different from the other three treatment blocks (fig. 2). We created no holdovers on the North Slope units because we expected that burning under dry conditions would result in nearly total consumption of the shallow duff layer.

We modified our sample design for the eight units burned in Washington in 1984 (Rink, Beaver Bar, and White Chuck Bench—Mount Baker-Snoqualmie NF; Breakeven and L142—Olympic NF; and High Divide, Little Deschutes, and Twin Harbor 896—Weyerhauser Timber Co.). Instead of altering fuel loading within a clearcut unit, we selected units with relatively consistent fuel loading and burned individual treatment blocks under different moisture conditions. We established 0.2-ha treatment blocks on two of the Washington units (four on Breakeven and three on White Chuck Bench) (fig. 2). Only one treatment block was established on each of the remaining units. The treatment blocks were burned at different times during the burning season to cover a range of moistures in large fuel.

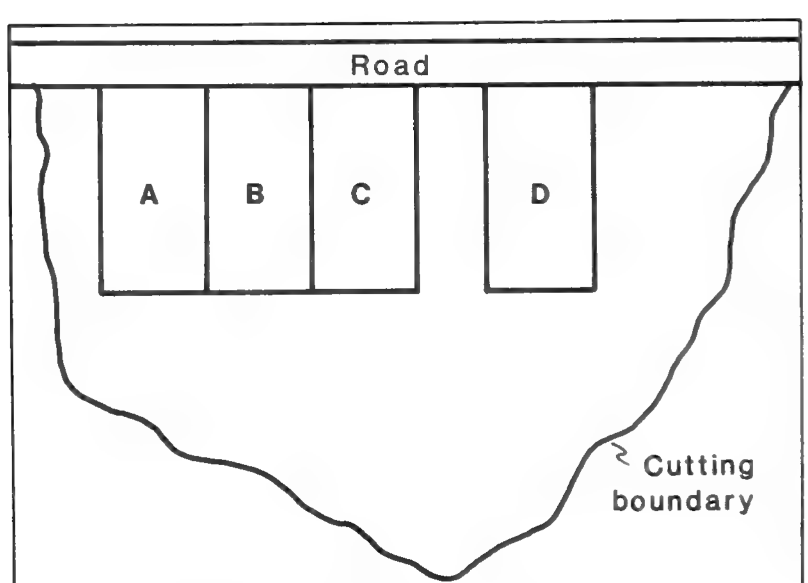

Figure 2.—Layout of treatment blocks within a cutting unit. In Oregon, A, B, and C burned simultaneously; D burned under different moisture conditions. In Washington, blocks burned under different moisture conditions.

We measured reduction in duff depth using procedures adapted from Beaufait and others (1977). We established 18 plots in a systematic grid to cover each treatment block. Around each plot we inserted 12 metal spikes and 4 tile pins[3] flush with the top of the duff layer. Duff for our purposes included the litter, fermentation, and humus layers. We measured duff reduction as the length of spike or pin exposed after the burn. We measured preburn duff depth as the length of spike or pin above mineral soil.

Duff consumption was calculated for each pin by multiplying duff depth reduction by one of two bulk density factors: for duff derived from litter or for duff derived from rotten wood. To determine duff density factors on each of nine treatment blocks (Breakeven, White Chuck, Beaver Bar, and Rink units), we collected 27 duff samples from a systematic grid. At each sample location a 12.7-cm by 12.7-cm by 10.0-cm metal box with open ends was inserted into the ground so the top of the box was flush with the top of the duff layer. Duff to a depth of 10.0 cm or to mineral soil, whichever was less, was removed from the box. If the duff layer was less than 10.0 cm deep, we measured the depth at each of the four corners of the box. The volume of each sample was calculated as the average depth times the sample area (12.7 cm by 12.7 cm). The samples were air dried for 2 weeks at 20 °C and weighed to the nearest gram. The bulk density of each sample (grams per cubic centimeter) was calculated as sample weight divided by sample volume. We then calculated the average bulk density of (1) all samples from litter-derived duff and (2) all samples from duff derived from rotten wood. Duff loading and consumption were then calculated by multiplying the duff depth at each pin by the appropriate bulk density (0.129 g/cm^3 for litter or 0.160 g/cm^3 for rot).

Several variables thought to affect duff consumption were also measured. Loading of the large fuels was estimated from a planar intersect inventory (Brown 1974). The sampling density consisted of 15.25-m transects located on a systematic grid of 80 points. Consumption of large fuels was measured as diameter reduction of 40 randomly chosen logs on the transects. Wires were tightly wrapped around the logs before burning and cinched up after burning. The wire lengths were measured and converted to diameter reduction. Diameter reduction was converted to fuel consumption using Ottmar (1984). The consumption of fine fuels was calculated as the difference between preburn and postburn loading. We determined large fuel moisture by removing two cross sections from each wired log and weighing the sections before and after drying at 105 °C for 24 hours.

[3]Tile pins were used to measure flaming and total duff consumption for a concurrent study.

Immediately prior to ignition of each treatment block we collected duff samples to determine the average percentage of moisture. We collected samples from the first 15 of the 18 plots in each treatment block. When a duff layer that was dry to the touch was present on top of a wet layer, we collected two samples—one from each layer—and measured the depth of the dry layer. If no distinct dry layer was present but duff dried with depth, we collected one sample each from the upper and lower half of the duff layer. When duff moisture seemed consistent throughout the profile (as is common with shallow duff layers), only one sample was taken on the plot. Each duff sample was a composite of samples collected from two locations within the plot area. On each plot, we sampled duff of similar kind (litter or rotten wood) and moisture content as that in which the duff pins were inserted. The samples were oven dried at 72 °C for 4 days to determine moisture content.

The treatment blocks were burned under a wide range of fuel moistures. We monitored environmental conditions using representative off-site Remote Automatic Weather Stations (RAWS) before burning each treatment block. Ignition of the 1983 units was delayed until the NFDR-Th was 25 percent or less and until days since last rain (1.3 cm or greater) were between 3 and 24 days. We believed this prescription would allow nearly complete consumption of fine fuels without allowing the duff to burn independently of large fuel. We burned the 1984 units over a range of fuel moisture conditions including spring (NFDR-Th greater than 25 percent), midsummer (NFDR-Th 22-25 percent), and late summer (NFDR-Th less than 22 percent). All burns were ignited by hand with strip head fires except the three Weyerhauser units, which were ignited using a helicopter. Data from the two sample designs, when pooled, provided information on duff consumption across a wide range of combinations of fuel loadings and moisture. A description of the 37 treatment blocks is presented in table 2. Moisture conditions at time of burn are shown in table 3.

Table 3—Moisture conditions at time of burn

Unit name (location)	Block	Moisture content at ignition: 7.6+ cm fuel	Upper duff	Lower duff	Dry layer depth	NFDR-Th	ADJ-Th	Days since rain
		-------- percent ------			cm			
Cataract (Siuslaw NF)	1	27	24	129	2.3	25	36	36
	2	34	16	178	1.7	25	36	36
	3	29	31	184	2.3	25	36	36
	4	32	61	183	1.0	28	37	7
Maria (Siuslaw NF)	1	23	25	113	2.1	25	36	38
	2	23	21	129	2.0	25	36	38
	3	31	35	155	1.9	25	36	38
	4	37	45	169	1.1	26	36	3
North Slope 6 (Rogue River NF)	1	31	30	---	---	21	30	7
	2	34	25	---	---	21	30	7
	3	33	24	---	---	21	30	7
North Slope 7 (Rogue River NF)	1	32	52	201	1.8	21	30	5
	2	31	31	---	---	21	30	5
	3	34	40	---	---	21	30	5
North Slope 8 (Rogue River NF)	1	29	67	---	---	21	30	6
	2	31	83	---	---	21	30	6
	3	37	45	---	---	21	30	6
Lower Grizzly (Umpqua NF)	1	37	19	142	1.6	24	34	4
	2	40	25	168	1.2	24	34	4
	3	33	58	203	1.8	24	34	4
	4	40	70	---	---	20	28	30
Yoncalla (Siuslaw NF)	1	35	113	---	---	24	33	13
	2	34	117	---	---	24	33	13
	3	32	111	---	---	24	33	13
	4	31	100	---	---	24	33	13
White Chuck (Mount Baker-Snoqualmie NF)	1	35	204	263	---	24	34	9
	3	27	46	213	1.8	20	30	27
Breakeven (Olympic NF)	1	38	257	308	---	22	32	15
	2	23	20	231	3.8	19	27	57
	3	37	22	290	2.6	18	27	30
	4	37	241	291	---	22	32	15
Beaver Bar (Mount Baker-Snoqualmie NF)	1	35	25	246	3.4	18	27	54
Rink (Mount Baker-Snoqualmie NF)	1	31	97	242	---	25	31	7
L 142 (Olympic NF)	1	45	56	265	3.7	22	32	18
High Divide (Weyerhauser)		32	40	245	1.0	26	31	5
Little Deschutes (Weyerhauser)		31	49	221	1.5	25	35	6
Twin Harbors #896 (Weyerhauser)		23	16	213	2.9	21	30	23

--- = not applicable.

Analytical Methods

Predictive equations for duff consumption and mineral soil exposure were developed with multiple linear regression. All coefficients reported are significant at the 99-percent confidence level (P = 0.01). Blocks were treated as independent observations because duff and fuel loadings were not consistent for any one treatment. By assuming that these observations were independent, we may have underestimated the residual variance relative to what would exist if all observations were truly independent.

One treatment block, White Chuck Bench #2, was excluded from the analysis because fine fuels and duff were so wet that the burn would not carry. This left 37 treatment blocks for analysis.

Based on relationships previously published (table 1) and our own experience, we thought that preburn measures of loading and moisture content of large fuels and duff moisture would be useful in predicting duff consumption. We used days since significant rainfall as a simple indication of the amount of drying that had taken place in the duff. Based on Stocks (1970), we assumed that 1.3 cm of rain was needed to raise the moisture content of duff to 120 percent. The wetting of duff to that moisture content should require the input of heat from woody fuel to drive off moisture before ignition of the duff is possible (Sandberg 1980). The moisture content of large fuels as predicted by NFDR-Th and ADJ-Th (a refinement of NFDR-Th for application in the Douglas-fir region (Ottmar and Sandberg 1985)) was included in our analysis. Fuel consumption and diameter reduction of large fuels were also included in the analysis.

Results

The results presented here are the best fitting equations with regard to correlation coefficient and standard error for our data. We will first relate duff consumption to fuel loading and moisture content, then improve our predictive capabilities by dividing the data into subsets by moisture regimes. We consider variables that were not helpful in predicting duff consumption in the Discussion. Fuel and duff consumption and exposure of mineral soil for each block are listed in table 4.

Table 4—Effects of prescribed fire on consumption and diameter reduction of woody fuels, consumption and depth reduction of duff, and exposure of mineral soil

		Woody fuel			Duff		
			>7.6 cm				
Unit name (location)	Block	0-7.6 cm consumed	Consumed	Diameter reduction	Consumed	Depth reduction	Mineral soil exposed
		----- Mg/ha -----		cm	--Mg/ha--	cm	percent
Cataract (Siuslaw NF)	1	15.9	4.2	3.9	42.6	3.2	32
	2	23.8	5.8	2.6	37.4	2.7	23
	3	11.7	14.6	4.7	45.1	3.2	30
	4	17.3	21.3	4.9	44.6	3.3	17
Maria (Siuslaw NF)	1	15.9	10.1	5.2	59.0	4.4	35
	2	8.7	4.5	3.2	47.3	3.6	36
	3	14.8	21.1	7.0	70.6	5.2	27
	4	22.9	10.3	2.7	26.9	2.0	7
North Slope 6 (Rogue River NF)	1	22.0	10.3	5.9	31.4	2.4	17
	2	18.6	13.9	4.7	30.5	2.3	29
	3	18.2	28.5	5.5	49.3	3.7	33
North Slope 7 (Rogue River NF)	1	18.6	6.7	5.5	28.2	2.1	16
	2	15.9	9.2	4.6	17.5	1.3	27
	3	18.6	14.3	5.0	22.9	1.7	22
North Slope 8 (Rogue River NF)	1	19.5	7.8	7.2	18.6	1.4	24
	2	21.1	28.9	7.3	35.6	2.7	20
	3	26.7	18.4	5.0	26.2	2.0	29
Lower Grizzly (Umpqua NF)	1	11.0	1.6	1.2	11.4	.8	2
	2	20.6	12.6	4.0	16.8	1.3	4
	3	17.9	5.8	1.4	13.5	1.0	2
	4	22.6	16.6	5.1	51.1	3.8	21
Yoncalla (Siuslaw NF)	1	12.8	9.2	3.6	17.3	1.3	10
	2	9.6	11.2	4.1	19.5	1.5	6
	3	16.1	16.6	3.1	25.3	1.9	7
	4	11.0	2.5	1.0	20.8	1.6	18
White Chuck (Mount Baker-Snoqualmie NF)	1	22.2	7.6	1.6	13.0	.9	0
	3	16.1	9.2	2.4	37.2	2.7	17
Breakeven (Olympic NF)	1	13.7	8.5	4.5	23.8	1.6	4
	2	16.4	23.1	4.7	60.5	3.9	18
	3	15.5	11.0	1.7	48.6	3.2	5
	4	17.9	22.6	2.8	30.7	2.1	3
Beaver Bar (Mount Baker-Snoqualmie NF)	1	17.3	10.3	2.1	47.7	3.3	11
Rink (Mount Baker-Snoqualmie NF)	1	23.3	53.4	8.8	45.7	3.3	19
L 142 (Olympic NF)	1	11.4	3.4	1.2	24.9	1.8	27
High Divide (Weyerhauser)		17.3	6.3	2.2	20.0	1.4	9
Little Deschutes (Weyerhauser)		16.6	8.7	1.9	39.5	2.9	3
Twin Harbors #896 (Weyerhauser)		17.7	26.5	3.8	51.1	3.6	21

Predicting Duff Consumption

We were able to predict duff consumption from the amount of large fuel (greater than 7.62 cm d.o.b.), the moisture content of that fuel, and the number of days since 1.3 cm of rainfall with limited success:

$$\text{DUFRED} = 1.209 + 0.435\ \text{L/LGMC} + 0.044\ \text{DAYS}\ , \qquad [1a]$$

$$R^2 = 0.53,\ s_{y \cdot x} = 0.76\ \text{cm},\ n = 37;\ \text{and}$$

$$\text{DUFCON} = 14.70 + 6.98\ \text{L/LGMC} + 0.65\ \text{DAYS}\ , \qquad [1b]$$

$$R^2 = 0.61,\ s_{y \cdot x} = 9.7\ \text{Mg/ha},\ n = 37;$$

where: DUFRED = duff depth reduction in centimeters,
DUFCON = duff consumption in megagrams per hectare,
L = preburn loading of large fuel in megagrams per hectare,
LGMC = moisture content of fuel 7.64 to 22.86 cm d.o.b. in percent, and
DAYS = the number of days since 1.3 cm of rainfall.

A graphic analysis indicated that two populations existed within our data set (fig. 3). Those units burned more than 25 days after 1.3 cm of rainfall from an individual storm system had more duff consumed for a given loading and moisture content of large fuels than those that were burned less than 25 days since rain. A linear regression using a dummy variable to designate the two groups showed a significant difference in intercept but not in slope (fig. 4):

$$\text{DUFRED} = 2.91 + 0.572\ \text{L/LGMC} - 1.54\ X\ , \qquad [2a]$$

$$R^2 = 0.60,\ s_{y \cdot x} = 0.70\ \text{cm},\ n = 37;\ \text{and}$$

$$\text{DUFCON} = 39.39 + 9.03\ \text{L/LGMC} - 22.26\ X\ , \qquad [2b]$$

$$R^2 = 0.66,\ s_{y \cdot x} = 9.0\ \text{Mg/ha},\ n = 37;$$

where: $X = 1$ when days since rain were less than 25; otherwise, $X = 0$.

The term L/LGMC is an approximation of the amount of fuel that is available to provide heat to dry and ignite the duff during a burn. Fuel consumption is a more direct measure of this heat. Our predictive power was improved by using fuel consumption as the independent variable (fig. 5):

$$\text{DUFRED} = 2.905 + 0.056\ \text{LGCON} - 1.691\ X, \quad [3a]$$

$$R^2 = 0.72,\ s_{y \cdot x} = 0.59 \text{ cm},\ n = 37; \text{ and}$$

$$\text{DUFCON} = 40.36 + 0.791\ \text{LGCON} - 24.39\ X, \quad [3b]$$

$$R^2 = 0.75,\ s_{y \cdot x} = 7.7 \text{ Mg/ha},\ n = 37;$$

where: LGCON = consumption of fuel larger than 7.62 cm d.o.b. in megagrams per hectare (Mg/ha), and

X = 1 when days since rain were less than 25, otherwise; X = 0.

LGCON can be predicted from algorithms presented by Sandberg and Ottmar (1983).

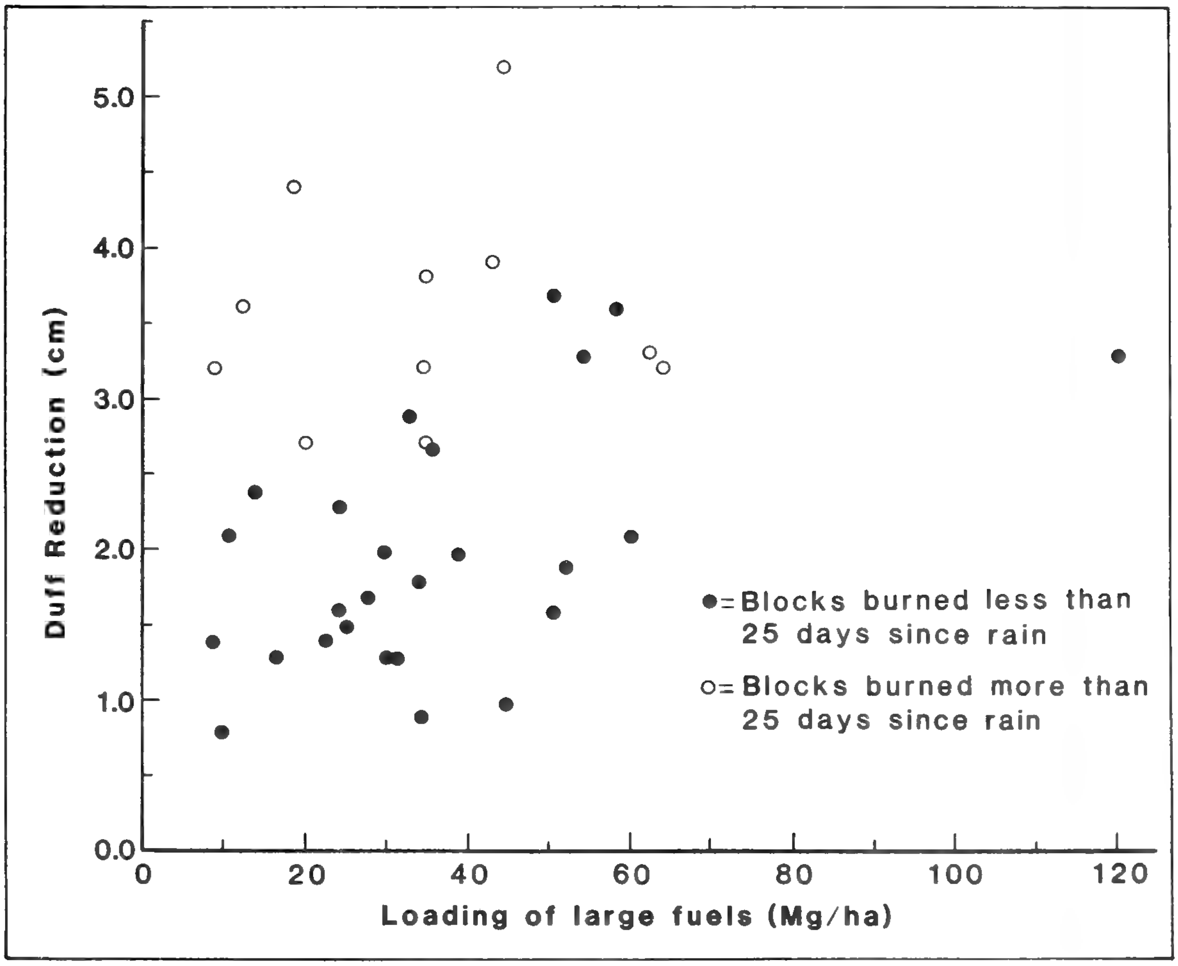

Figure 3.—Relationship of duff reduction and loading of large fuels.

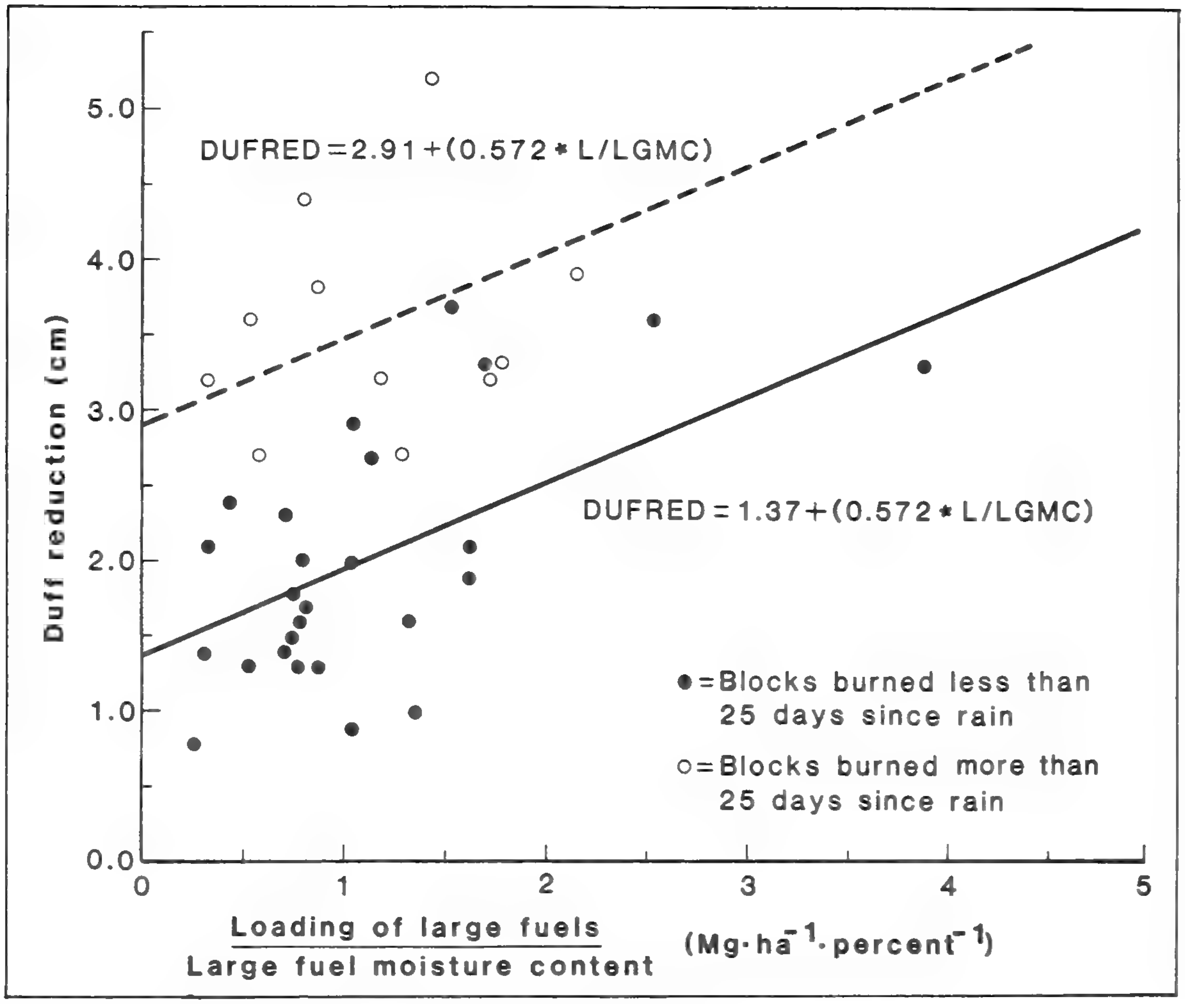

Figure 4.—Relationship of duff reduction, loading, and moisture content of large woody fuels (greater than 7.62 cm d.o.b.).

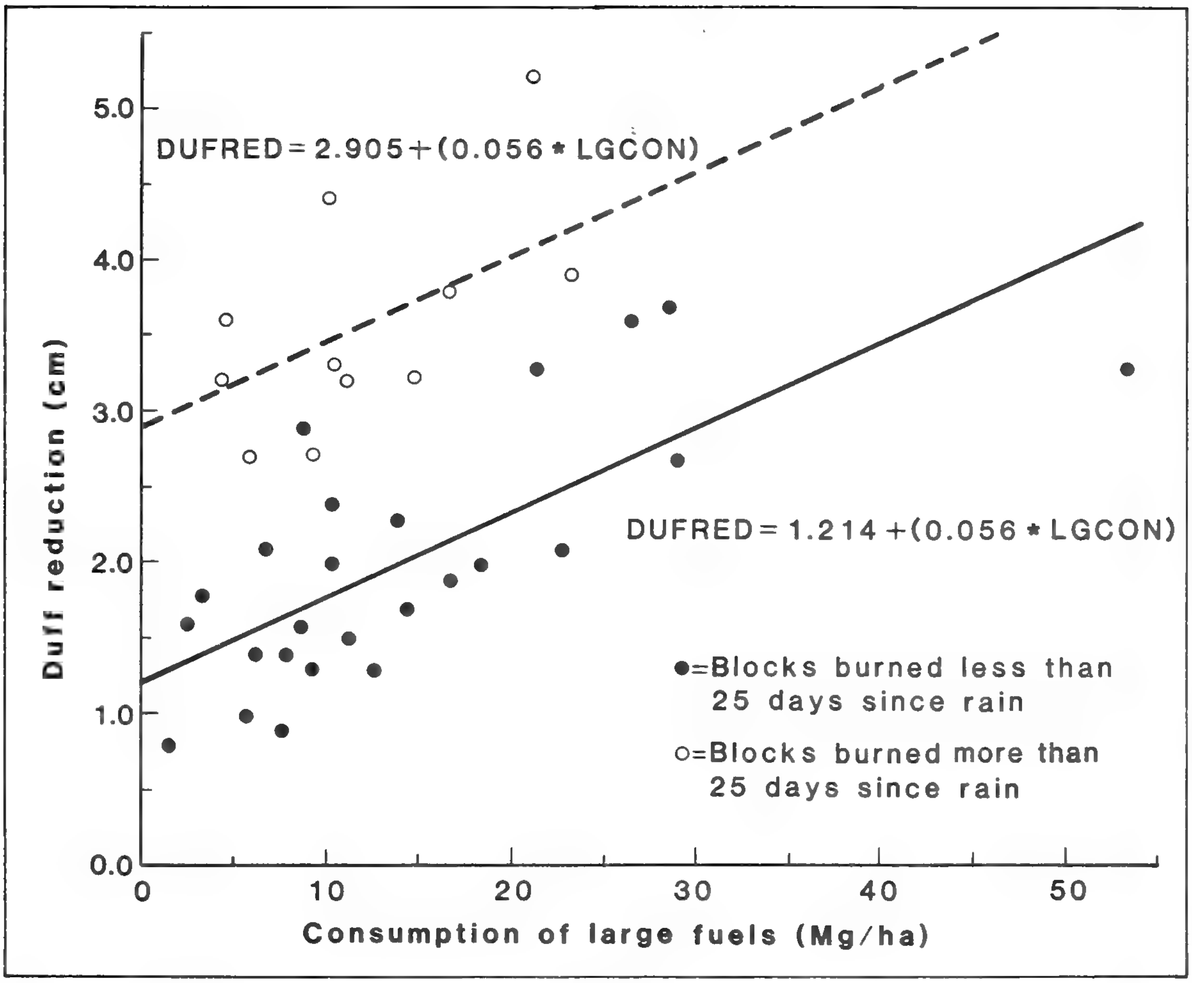

Figure 5.—Relationship of duff reduction and consumption of large fuels.

Equations were then developed separately for both groups. Duff consumption was predicted from large fuel consumption for the first group (less than 25 days since rainfall). Duff consumption for the second group (25 or more days since rainfall) was correlated more strongly with fire duration, as measured by fuel diameter reduction, than with fuel consumption.

The following equations predict duff consumption for units where consumption is dependent on moisture and consumption of large woody fuels (less than 25 days since rain):

$$DUFRED = 1.295 + 1.659\ LGCON/LGMC, \qquad [4a]$$

$$R^2 = 0.58,\ s_{y \cdot x} = 0.57\ \text{cm},\ n = 26;\ \text{and}$$

$$DUFCON = 17.01 + 23.26\ LGCON/LGMC, \qquad [4b]$$

$$R^2 = 0.60,\ s_{y \cdot x} = 7.7\ \text{Mg/ha},\ n = 26.$$

The presence or absence of a distinct upper dry layer in the duff also influenced the amount of duff consumed. A further split based on moisture profile gave the following results.

For units **without** a distinct dry layer of duff:

$$DUFRED = 1.020 + 2.186\ LGCON/LGMC, \qquad [5a]$$

$$R^2 = 0.58,\ s_{y \cdot x} = 0.45\ \text{cm},\ n = 16;\ \text{and}$$

$$DUFCON = 13.89 + 29.03\ LGCON/LGMC, \qquad [5b]$$

$$R^2 = 0.59,\ s_{y \cdot x} = 5.8\ \text{Mg/ha},\ n = 16.$$

For units **with** a distinct dry layer:

$$DUFRED = 1.159 + 1.316\ LGCON/LGMC + 0.041\ DAYS, \qquad [6a]$$

$$R^2 = 0.65,\ s_{y \cdot x} = 0.70\ \text{cm},\ n = 10;\ \text{and}$$

$$DUFCON = 15.26 + 18.35\ LGCON/LGMC + 0.64\ DAYS, \qquad [6b]$$

$$R^2 = 0.68,\ s_{y \cdot x} = 9.4\ \text{Mg/ha},\ n = 10.$$

For units where consumption was dependent on fuel moisture (more than 25 days since rain), duff consumption was predicted from the square root of the diameter reduction of the large fuels (DRED):

$$DUFRED = 0.839 + 1.413\sqrt{DRED}, \qquad [7a]$$

$$R^2 = 0.64,\ s_{y \cdot x} = 0.47\ \text{cm},\ n = 11;\ \text{and}$$

$$DUFCON = 16.19 + 17.41\sqrt{DRED}, \qquad [7b]$$

$$R^2 = 0.51,\ s_{y \cdot x} = 7.5\ \text{Mg/ha},\ n = 11;$$

where: DRED is measured in centimeters.

We were not able to predict duff consumption from either the NFDR-Th or ADJ-Th fuel moisture estimates or from the measured fuel moisture (R^2 less than 0.2).

Predicting the Amount of Soil Exposed by Burning

The amount of soil exposed after a burn depends on the amount of soil exposed before the burn, the depth of the duff covering the rest of the soil, and the amount of duff consumed during the fire. We were able to predict soil exposed from average duff depth before burn and the number of days since last rainfall:

$$\%EXPOSED = 28.0 - 2.4\ BEFDUFF + 0.43\ DAYS\ , \qquad [8]$$

$$R^2 = 0.58,\ s_{y \cdot x} = 7.2 \text{ percent},\ n = 37;$$

where: %EXPOSED = the amount of mineral soil exposed during the burn,
BEFDUFF = the average duff depth before burn in centimeters, and
DAYS = the number of days since 1.3 cm of rainfall.

Deeper duff depths will have a minimal amount of soil exposed by the burn. For example, for a unit with a preburn duff depth of 16 cm (the upper end of our data range), more than 25 days since rain must elapse before any additional soil is exposed. Our predictive capabilities were not improved by adding preburn soil exposure or loading to the equation.

Discussion

We were successful in predicting duff consumption from preburn loading and moisture content of large fuels and days since rainfall. As expected, when the duff was wet, duff consumption could be predicted from fuel consumption. As the duff dried, consumption was more dependent on fire duration, as measured by diameter reduction of large fuels. We were able to improve our predictive power by dividing the data set into those units where duff reduction was dependent on fuel consumption and those where it was dependent on fire duration based on the number of days since significant precipitation. We also separated the units that were dependent on fuel consumption into those with and those without a distinct upper dry layer of duff. We were not able to predict duff reduction directly from preburn loading for all groups.

We did not stratify the selection of units by these classifications. By selecting a subsample of the data instead of sampling units by class, we may have biased samples within the classes. The scope of inference for equations 3-7 is thereby reduced. The reader is cautioned to consider the range of data for which each equation was developed.

The predictive power of the equations presented here are within the range for those previously published. We can only make a direct comparison of duff depth reduction with Sandberg (1980) for those units burned more than 25 days since rain. Although our correlation coefficient is not as high as his, the standard error is similar for the same sample size.

Although we sampled for duff moisture on all blocks and obtained satisfactory estimates of average duff moisture for the blocks, neither upper nor lower duff moisture appeared to enhance our ability to predict duff consumption. We suspect that this was due to the high variability of duff moisture within a treatment block. Duff moisture data might prove useful if they were in frequency form and were linked with duff depth and bulk density information for individual samples.

We were not able to show a correlation of duff consumption with NFDR-Th or ADJ-Th because our data did not span a large enough range of predicted moisture contents of woody fuels. Predicted moisture content of large fuels was purposefully constrained in the Oregon units to isolate effects of fuel loading. Several of the blocks in Washington had no slope, which reduced the amount of consumption of large fuel that would be expected for a given NFDR-Th based on Sandberg and Ottmar (1983).

Moisture content and consumption of large fuels were estimated from measuements taken at the study areas. If predicted values for these variables are used in the equations (such as values obtained through the National Fire-Danger Rating System), other sources of error will be introduced into the equations beyond what we report here. Use of predicted values should reduce the confidence one has in the resulting estimate of duff reduction or consumption.

We were not able to significantly reduce error by omitting those pins that were in mineral soil, in stumps, or in logs before burn. This is probably because of the high variability of duff depth and density across a unit.

The equations presented in this paper should be used under the conditions they were developed for. These equations cover units with average duff depth greater than 3 cm. For units with shallow duff layers, duff moisture will be drier and more consistent over the unit. The number of days since rain that separates our first population (loading dependent) from our second (moisture dependent) will be less than 25. Duff reduction on units with shallow duff depths may be predictable from Sandberg's (1980) equations using NFDR-Th.

We have not incorporated data for extremes in fuel and duff moisture. Under very dry conditions, when the upper 5 cm of duff has less than a 30-percent moisture content, the duff will burn independently of the surface fuels. Under very moist conditions, much of the area will not ignite and the smoldering period will be reduced. Sustained dry winds or precipitation during the burn will have similar effects.

Application

Forest managers need the ability to predict duff reduction and mineral soil exposure to meet objectives for site preparation and productivity. The amount of duff consumed during a prescribed fire depends on loading and moisture content of woody fuels, the moisture profile of the duff, and the duration of heat supplied to the duff by the burning woody fuel. Managers can meet their objectives by (1) specifying the amount of woody fuels to remain on site after harvest, (2) scheduling the burn for specific fuel moistures, or (3) using a combination of both (1) and (2). Equation 2 can be used to evaluate the effect of removing large fuels before burn on subsequent duff consumption. Equation 4 can be used to set prescriptions once a given fuel loading is determined. Equations 5, 6, and 7 can be used to predict duff consumption on a unit for a particular day. Three management scenarios for a hypothetical clearcut unit are presented below to demonstrate the use of these equations.

Hypothetical Clearcut Unit

Location: Mount Hood National Forest
Slope: 30 percent
Aspect: west
Average duff depth: 9.1 cm
Mineral soil exposure: 20 percent
Fuel type: Douglas-fir/western hemlock
Woody fuels: all material larger than 20.3 by 240 cm has been removed
Fuel loading:

Size class		Dry weight		Root mean square diameter (d)	
cm	in	Mg/ha	tons/acre	cm	in
0-7.6	0-3	14.4	6.4		
7.6-15.2	3-6	11.9	5.3		
15.2-22.9	6-9	11.2	5.0		
22.9-50.8	9-20	54.5	24.3		
50.8+	20+	30.0	13.4		
All 7.6+	All 3+	107.6	48.1	18.0	7.1
All woody fuels		122.0	54.4		
Duff		150.2	67.0		
Total fuel loading		272.0	121.3		

Scenario 1: Influence woody fuel loading to achieve management objectives.—The manager can affect duff reduction by altering the loading of large woody fuels. For example, suppose the hypothetical unit is burned 15 days after rainfall with its present fuel loading and with large fuel moisture content at 28 percent. Equation 2a shows that duff depth would be reduced by 3.6 cm:

$$\begin{aligned} \text{DUFRED} &= 2.91 + 0.572\ \text{L/LGMC} - 1.54\text{X} \\ &= 2.91 + 0.572\ (107.6/28) - 1.54 \\ &= 3.6\ \text{cm}. \end{aligned} \qquad [2a]$$

The loading of large woody fuels can be reduced by yarding all pieces larger than a specified size (for example, 10 by 131 cm) from the unit. Because piece size is specified in terms of length as well as diameter, and length is rarely measured in fuel inventories, one cannot predict the exact weight of fuels that would remain on the unit following yarding. In this example, we assume that 60 percent of the large fuel is removed, which reduces loading from 107.6 Mg/ha to 43.0 Mg/ha. Burning under the same moisture conditions as in the previous example would result in a reduction in duff depth of 2.2 cm—1.4 cm less than with the original fuel loading:

$$\begin{aligned} \text{DUFRED} &= 2.91 + 0.572\ \text{L/LGMC} - 1.54\text{X} \\ &= 2.91 + 0.572\ (43.0/28) - 1.54 \\ &= 2.2\ \text{cm.} \end{aligned} \tag{2a}$$

Scenario 2: Influence moisture conditions to achieve objectives.—The manager can also affect duff reduction by influencing the moisture conditions the unit is burned under. This can be accomplished by burning a specified number of days after rainfall or by burning when large woody fuels have a specific moisture content.

1. Management objective: Retain an average duff depth of 5 cm.—The manager can use equation 4a to determine the lowest fuel moisture under which the burn can take place and still meet objectives. Because we want to retain an average duff depth of at least 5 cm, our goal is to reduce duff depth by no more than 4.1 cm ((maximum duff reduction during the burn) = (preburn duff depth) - (postburn duff depth) = 9.1 - 5.0 = 4.1 cm):

$$\text{DUFRED} = 1.295 + 1.659\ \text{LGCON/LGMC}\ ; \tag{4a}$$

where:
$$\begin{aligned} \text{LGCON} &= \text{L} \times \text{VRED}, \\ \text{VRED} &= 1 - (\text{d} - \text{DRED})^2/\text{d}^2 \text{ (Sandberg and Ottmar 1983)}, \\ \text{DRED} &= 14.43 - 0.274\ \text{LGMC (Sandberg and Ottmar 1983)}, \\ \text{d} &= 12.0 \text{ cm (reduced from 18.0 cm by yarding), and} \\ \text{L} &= 43.0 \text{ Mg/ha (reduced from 107.6 cm by yarding—see scenario 1).} \end{aligned}$$

For LGMC = 20 percent:
DRED = 9.0 cm,
VRED = 0.94,
LGCON = 43.0 x 0.94 = 40.4 Mg/ha, and
DUFRED = 4.6 cm.

For LGMC = 35 percent:
DRED = 4.8 cm,
VRED = 0.64,
LGCON = 43.0 x 0.64 = 27.5 Mg/ha, and
DUFRED = 2.6 cm.

For LGMC = 23 percent:
DRED = 8.1 cm,
VRED = 0.89,
LGCON = 43.0 x 0.89 = 38.3 Mg/ha, and
DUFRED = 4.1 cm.

To meet the management objective in this example, the burn must take place when large woody fuel moisture is at least 23 percent. If it does not, duff depth will be reduced by more than the desired 4.1 cm, which will result in an average duff depth on the unit of less than 5 cm.

2. Management objective: Remove 5 cm of duff to ensure that seedlings are planted with their roots in mineral soil.—Suppose our example unit has an average duff depth of 15 cm. Local experience has led the manager to believe that planting crews do not do an adequate job when average duff depth exceeds 10 cm. One of the objectives for burning this unit is to reduce duff depth by 5 cm. However, large fuel moistures seldom get below 18 percent during the burn season in this area. Can this objective be met if moisture content of large fuels is larger than 18 percent?

For LGMC = 18 percent:
- DRED = 9.0 cm,
- VRED = 0.94,
- LGCON = 43.0 x 0.94 = 40.4 Mg/ha, and
- DUFRED = 1.295 + 1.659 (40.4/18) = 5.1 cm.

The manager's chances of obtaining the desired amount of duff consumption are low. Had the unit not been gross yarded, the chances of reducing the duff layer by 5 cm would have been much better:

For LGMC = 28 percent:
- DRED = 6.8 cm,
- VRED = $1 - (18 - 6.8)^2/18^2 = 0.61$,
- LGCON = 107.6 x 0.61 = 65.6 Mg/ha, and
- DUFRED = 1.295 + 1.659 (65.6/28) = 4.9 cm.

Scenario 3: Predict the effects of burning out of prescription.—It is not unusual for regulatory agencies to permit burning on days when priority units are not in prescription. The manager can use either equation 4a or 7a to determine the magnitude of effects from burning out of prescription. In this case, the manager cannot alter either fuel loading or moisture. If the unit had rain less than 25 days ago, the manager would use equation 4a to predict duff depth reduction. The effect of burning our example unit at 20 days since rain with a fuel moisture of 20 percent would be a reduction of duff depth of 4.6 cm (see calculations under scenario 2, management objective 1).

If 25 or more days have elapsed since rainfall, equation 7a can be used to predict duff reduction. For example, if large woody fuel moisture content is 18 percent and the unit is burned 30 days after rainfall, duff depth would be reduced by 5.2 cm:

$$\begin{aligned}\sqrt{DRED} &= \sqrt{14.43 - 0.274\ LGMC} \\ &= 3.1\ \text{cm; and}\end{aligned}$$

$$\begin{aligned}DUFRED &= 0.839 + 1.413\sqrt{DRED} \\ &= 0.839 + 1.413\ (3.1) \\ &= 5.2\ \text{cm.}\end{aligned} \qquad [7a]$$

Under these conditions, mineral soil would be exposed on 19 percent of the unit during the burn, resulting in a total postburn exposure of 39 percent:

$$\begin{aligned}\%\ EXPOSED &= 28.0 - 2.4\ BEFDUFF + 0.43\ DAYS \\ &= 28.0 - 2.4\ (9.1) + 0.43\ (30) \\ &= 19\ \text{percent.}\end{aligned} \qquad [8]$$

Conclusions

Our results suggested that duff consumption from prescribed fire can be reduced by reducing fuel loading before burning, by burning under moist conditions, or both. In some areas, smoke management concerns allow for relatively few days to burn clearcuts during the year. In those cases, removing additional woody fuel during or after harvest will broaden the moisture conditions under which prescriptions for duff consumption can be met and, hence, allow the manager more flexibility in scheduling burns. Costs of wood removal may be offset by reductions in costs of burning and mitigation of negative effects of burning out of prescription. For the range of conditions in this study, the effect of fuel loading on duff consumption decreased with the number of days since rainfall. The amount of duff consumed during burns conducted more than 25 days since rain was dependent on fire duration, as measured by diameter reduction of large fuels, and hence, was dependent on the moisture content of large woody fuels.

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English Equivalents

When you know:	Multiply by:	To find:
Centimeters (cm)	0.3937	inches
Meters (m)	3.2808	feet
Hectares (ha)	2.4711	acres
Grams (g)	0.0350	ounces
Kilograms (kg)	2.2046	pounds
Kilograms/hectare (kg/ha)	0.8926	pounds/acre
Megagrams/hectare (Mg/ha)	0.4453	tons/acre
Celsius	1.8 then add 32	Fahrenheit

Equations in English Units

$$DUFRED = 0.48 + 0.38\ L/LGMC + 0.02\ DAYS \text{ , and} \quad [1a]$$

$$DUFCON = 6.56 + 6.98\ L/LGMC + 0.29\ DAYS \text{ ;} \quad [1b]$$

where: DUFRED = duff depth reduction in inches,
DUFCON = duff consumption in tons per acre,
L = preburn loading of large fuel in tons per acre,
LGMC = moisture content of fuel 3.1 to 9.0 inches d.o.b. in percent, and
DAYS = days since continuous rainfall greater than 0.5 in.

$$DUFRED = 1.14 + 0.51\ L/LGMC - 0.61\ X \text{ , and} \quad [2a]$$

$$DUFCON = 17.57 + 9.03\ L/LGMC - 9.91\ X \text{ ; and} \quad [2b]$$

$$DUFRED = 1.14 + 0.05\ LGCON - 0.67\ X \text{ , and} \quad [3a]$$

$$DUFCON = 18.00 + 0.79\ LGCON - 10.88\ X \text{ ;} \quad [3b]$$

where: LGCON = consumption of fuel larger than 3.0 inches d.o.b. in tons per acre, and
X = 1 when days since rain were less than 25;otherwise, X = 0.

The following equations predict duff consumption for units where consumption is independent of fuel loading (less than 25 days since rain):

$$DUFRED = 0.51 + 1.46\ LGCON/LGMC \text{ , and} \quad [4a]$$

$$DUFCON = 7.59 + 23.26\ LGCON/LGMC \text{ .} \quad [4b]$$

For units **without** a dry layer of duff:

$$DUFRED = 0.40 + 1.93\ LGCON/LGMC \text{ , and} \quad [5a]$$

$$DUFCON = 6.20 + 29.03\ LGCON/LGMC \text{ .} \quad [5b]$$

For units **with** a distinct dry layer:

$$DUFRED = 0.46 + 1.16\ LGCON/LGMC + 0.02\ DAYS \text{ , and} \quad [6a]$$

$$DUFCON = 6.81 + 18.35\ LGCON/LGMC + 0.29\ DAYS \text{ .} \quad [6b]$$

For units where consumption is dependent on fuel moisture (more than 25 days since rain), duff consumption can be predicted from the square root of the diameter reduction of the large fuels (DRED):

$$DUFRED = 0.33 + 2.80 \sqrt{DRED}\text{, and} \qquad [7a]$$

$$DUFCON = 7.22 + 39.14 \sqrt{DRED}\text{;} \qquad [7b]$$

where DRED is measured in inches.

Predicting the amount of soil exposed by burning:

$$\%EXPOSED = 25.77 - 8.71\ BEFDUFF + 0.43\ DAYS\text{;} \qquad [8]$$

where BEFDUFF is the average duff depth before burning, in inches.

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Abbreviations

ADJ-Th—predicted moisture content of large fuels adjusted for Douglas-fir.

BEFDUFF—average depth of duff before burn in millimeters.

DAYS—days since at least 1.3 cm of rainfall within a 24-hour period.

DMC—Canadian Duff Moisture Index.

DRED—diameter reduction of fuels greater than 7.6 cm d.o.b.

DRYDEPTH—depth of the distinct dry layer of duff.

DUFCON—consumption of duff during burn in megagrams per hectare.

DUFRED—reduction in average duff depth due to burn.

%EXPOSED—the percentage of area on a unit where the A-horizon is exposed by consumption of duff during the burn.

L—loading of fuels larger than 7.6 cm d.o.b. before burn.

LGCON—consumption of fuels greater than 7.6 cm d.o.b. in megagrams per hectare.

LGMC—measured moisture content of large fuels at time of burn in percent.

NFDR-Th—predicted moisture content of large fuels from National Fire-Danger Rating System in percent.

UDMC—measured moisture content of the upper layer of duff in percent. The upper layer is either the pronounced dry layer or the upper half of the duff depending on the presence or lack of a dry layer.

VRED—volume reduction of large fuels in percent.

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Little, Susan N.; Ottmar, Roger D.; Ohmann, Janet L. Predicting duff consumption from prescribed burns on conifer clearcuts in western Oregon and western Washington. Res. Pap. PNW-362. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station; **1986.** 29 p.

Duff consumption by fire was studied on 15 cable-yarded clearcut units in western Oregon and western Washington. Equations are presented that predict duff consumption (in depth reduction and weight loss) from loading, consumption, and moisture of large fuels, and days since significant precipitation. When more than 25 days elapsed since 1.3 cm rainfall, the effect of large fuel loading on duff consumption diminished. Duff consumption was dependent on the diameter reduction of large fuels when there had been no rain for at least 25 days. The results indicated that duff consumption can be reduced by removing large fuel before the burn, scheduling the burn under moist conditions, or both. Methods are demonstrated to prescribe the proper level of fuel removal and moisture regime at time of burn to achieve a given level of duff consumption.

Keywords: Duff consumption, duff reduction, fire effects, prescribed burning, duff moisture, mineral soils, clearcuts.

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